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BREMSSTRAHLUNG PRODUCTION

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DIVISION OF ELECTRONIC PRODUCTS

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BREMSSTRAHLUNG PRODUCTION

David G. Brown

Radiation Measurements and Calibration Branch
Division of Electronic Products

July 1970

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Environmental Health Service
Bureau of Radiological Health
Rockville, Maryland 20852

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FOREWORD

The Bureau of Radiological Health, formerly the National Center for Radiological Health, continues to carry out a national program designed to reduce the exposure of man to hazardous ionizing and non-ionizing radiation.

Within the Bureau, the Division of Electronic Products (1) develops and administers performance standards for radiation emissions from electronic products, (2) studies and evaluates emissions of and conditions of exposure to electronic product radiation and intense magnetic fields, (3) conducts or supports research, training, development, and inspections to control and minimize such hazards, and (4) tests and evaluates the effectiveness of procedures and techniques for minimizing such exposures.

The Bureau publishes its findings in Radiological Health Data and Reports (a monthly publication), Public Health Service numbered reports, appropriate scientific journals, and technical report series for the Bureau's divisions, offices, and laboratories.

The technical reports of the Division of Electronic Products (DEP) allow comprehensive and rapid publishing of the results of intramural and contractor projects. The reports are distributed to State and local radiological Health program personnel, Bureau technical staff, Bureau advisory committee members, university radiation safety officers, libraries and information services, industry, hospitals, laboratories, schools, the press, and other interested individuals. These reports are also included in the collections of the Library of Congress and the Clearinghouse for Federal Scientific and Technical Information.

I encourage the readers of these reports to inform the Bureau of any omissions or errors. Your additional comments or requests for further information are also solicited.

John C. Villforth
Director
Bureau of Radiological Health

PREFACE

In the "Radiation Control for Health and Safety Act of 1968" (Public Law 90-602), Congress provided "for the establishment by the Secretary, DHEW of an electronic radiation control program which shall include.....the undertaking by public and private organizations of research and investigation into the effects and control of such electronic product radiation emissions." Since bremsstrahlung accounts for most of the ionizing radiation originating in electronic products, the Act clearly requires that research be carried out on this type of radiation. For this reason, the Division of Electronic Products (DEP), Bureau of Radiological Health, has initiated a study of bremsstrahlung production.

The DEP effort has included a literature survey to determine the current state of knowledge concerning the elementary bremsstrahlung process and an experimental program to remedy the deficiencies discovered during the survey. This report summarizes the results of the DEP program to the present time.

Robert L. Elder, Sc.D.
Acting Director
Division of Electronic Products

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ABSTRACT

An understanding of bremsstrahlung production is basic to the understanding of x radiation from electronic products. For this reason the Division of Electronic Products has conducted a bremsstrahlung literature survey and has begun a program of experimental research on bremsstrahlung production. The literature survey revealed severe deficiencies in present knowledge about bremsstrahlung, indicating that the DEP program is urgently needed.

BREMSSTRAHLUNG PRODUCTION

1. INTRODUCTION

Bremsstrahlung, literally "braking radiation" in German, is produced when a charged particle is deflected in an electric or magnetic field. This type of x radiation commonly originates in electronic components, especially when high voltages are present. Electrons are accelerated through a potential difference, collide with the atoms of some structure in the component, are deflected in the electric fields of the atoms making up the structure; and bremsstrahlung is produced.

At most, only a few percent of the energy of the initial electrons goes into bremsstrahlung; the rest of the energy, for the most part, is converted into very low energy quanta and appears as heat. The exception to this is fluorescence radiation which, however, is usually produced far less copiously. Thus, bremsstrahlung accounts for most of the x rays from electronic products.

Since x-ray production has been studied for over half a century, it might be assumed that all of the characteristics of bremsstrahlung would be well understood by now. That, unfortunately, is not the case. A literature survey was undertaken to discover the current state of knowledge, and it was found that at present neither the experimental determination nor the theoretical calculation of bremsstrahlung characteristics are particularly satisfactory. The findings of this survey are reported in some detail in sections 3 and 4.

In view of this lack of reliable information, a project has been undertaken by DEP for experimental study of the basic bremsstrahlung process. The way in which this experiment will be carried out is outlined in section 5.

2. THE BREMSSTRAHLUNG PROCESS

Figure 1 illustrates the fundamental bremsstrahlung process.

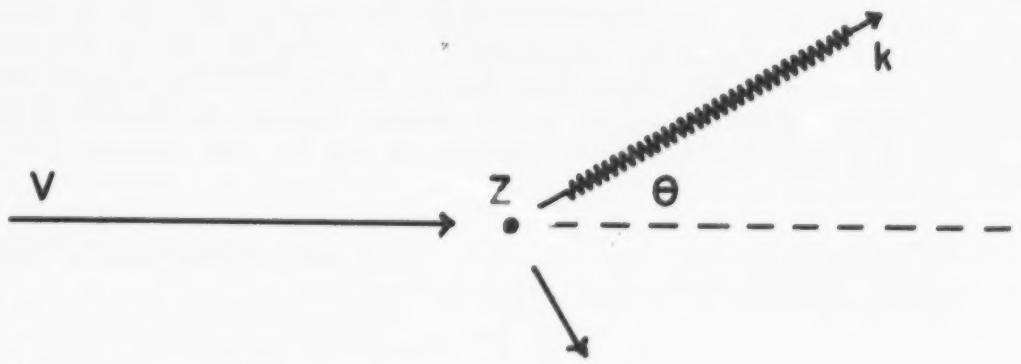

Figure 1. The fundamental process.

An electron with kinetic energy V impinges upon a target atom of atomic number Z, is scattered, and emits a photon of energy k at an angle θ with respect to the direction of the incident electron. The polarization of the incident electron and bremsstrahlung photon and the polarizations and momenta of the recoil nucleus and scattered electron are neglected, only the initial electron beam energy and outgoing photon energy and angle being detected. This is the basic bremsstrahlung process and the only aspect of bremsstrahlung which will be considered in the present report. Thus, there are four variables of interest: V, Z, k, and θ, with the further restriction that at the present time initial kinetic energies above 100 keV will not be considered.

This elementary process can be studied by using targets sufficiently thin that no significant fraction of the photons produced is prevented from leaving the target and being detected, and conversely, that almost all of the photons leaving the target result from primary bremsstrahlung interactions; i.e., the target is so thin that multiple scattering of the incident electrons and absorption of the outgoing photons may be neglected. For this reason the experimental study of the basic bremsstrahlung process is called "thin-target" bremsstrahlung.

Of course, for radiation from an electronic product, filtration and thick-target considerations of multiple scattering, target self-absorption, and secondary x-ray production must all be taken into account. The basic bremsstrahlung cross sections are fundamental to an understanding of this process, however, and will be studied before the thick-target aspects are considered. In the present report primary emphasis will be placed on thin-target experiments (1-15). Thick-target results (16-25) will be mentioned only insofar as they are of historical interest, having allowed predictions to be made concerning the outcome of the later, more difficult thin-target work. For a more comprehensive treatment of the energy loss of electrons in matter reference may be made to several standard works, such as those by Evans (26) and by Bethe and Ashkin (27).

3. THIN-TARGET BREMSSTRAHLUNG EXPERIMENTS: LITERATURE SURVEY

In order to ascertain what had been learned about bremsstrahlung in previous experiments, a literature survey was performed for articles on thin-target bremsstrahlung experiments at energies below 100 keV. The results of this survey are described below for each of the experimental parameters mentioned previously; i.e., atomic number Z, electron kinetic energy (electron gun voltage[1]) V, photon energy k, and photon production

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[1] With the stable d-c power supplies used in these experiments, this equivalence is for all practical purposes exact.

angle θ. In addition, a few general comments concerning the adequacy of the experiments carried out up to the present appear in the final subsection.

In the following sections results are given in terms of the bremsstrahlung energy cross-section (hence forth called the bremsstrahlung intensity) differential in photon energy and production angle -- $kd^2\sigma/dkd\Omega$. This is the energy density in photons of energy k and angular coordinates Ω [2] per incident electron, per target atom/unit area. Its units are millibarns (mb) per steradian (one mb = 10^{-27} cm^2).

3.1 ATOMIC NUMBER (Z) DEPENDENCE

Early experiments on thick targets (17-19) indicated a linear dependence of total intensity on atomic number, although with perhaps some deviation correlated with the periodic table (19). Since the electron range in the target is approximately inversely proportional to Z, this implies a Z^2 proportionality for thin-target bremsstrahlung; i.e., if an electron in going 1/Z as far emits Z times as much radiation, then the radiation cross section must vary as Z^2.

This prediction has been born out fairly well by the thin-target experiments. The most definitive experimental evidence is that of Fischer and Hoffman (1), and is shown in figure 2. They obtained the relation

$$i_k = (4.1 \pm 1.1) \times Z^{2.0 \pm 0.1}$$

where i_k is the bremsstrahlung intensity in mb/steradian at V=50 keV, k=20 keV, θ=90°, using targets of Al, Mn, Cu, Se, Ag, and Sn (Z between 13 and 50). Previous work by Amrehn (5) had indicated a steeper than Z^2 rise for small Z. As shown in figure 2, this behavior is predicted by the nonrelativistic theory in order to determine the validity of the Z^2 dependence, further experimental work is necessary, especially for small Z.

Amrehn had found it necessary to reduce his value for Al by 30 percent, because of the probable presence of additional oxygen as Al_2O_3, in order to obtain good agreement with theory. Motz and Placious (3) experienced the reverse difficulty, and invoked retardation and screening effects to explain the surprisingly low values obtained experimentally for Al, also shown in figure 2. Since this is the only point allowing a comparison between the absolute normalizations of references (1) and

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[2] $d\Omega = d\phi\, d\cos\theta$, where θ is the photon production angle and φ the (arbitrary) angle of the plane of the reaction with respect to some fixed plane.

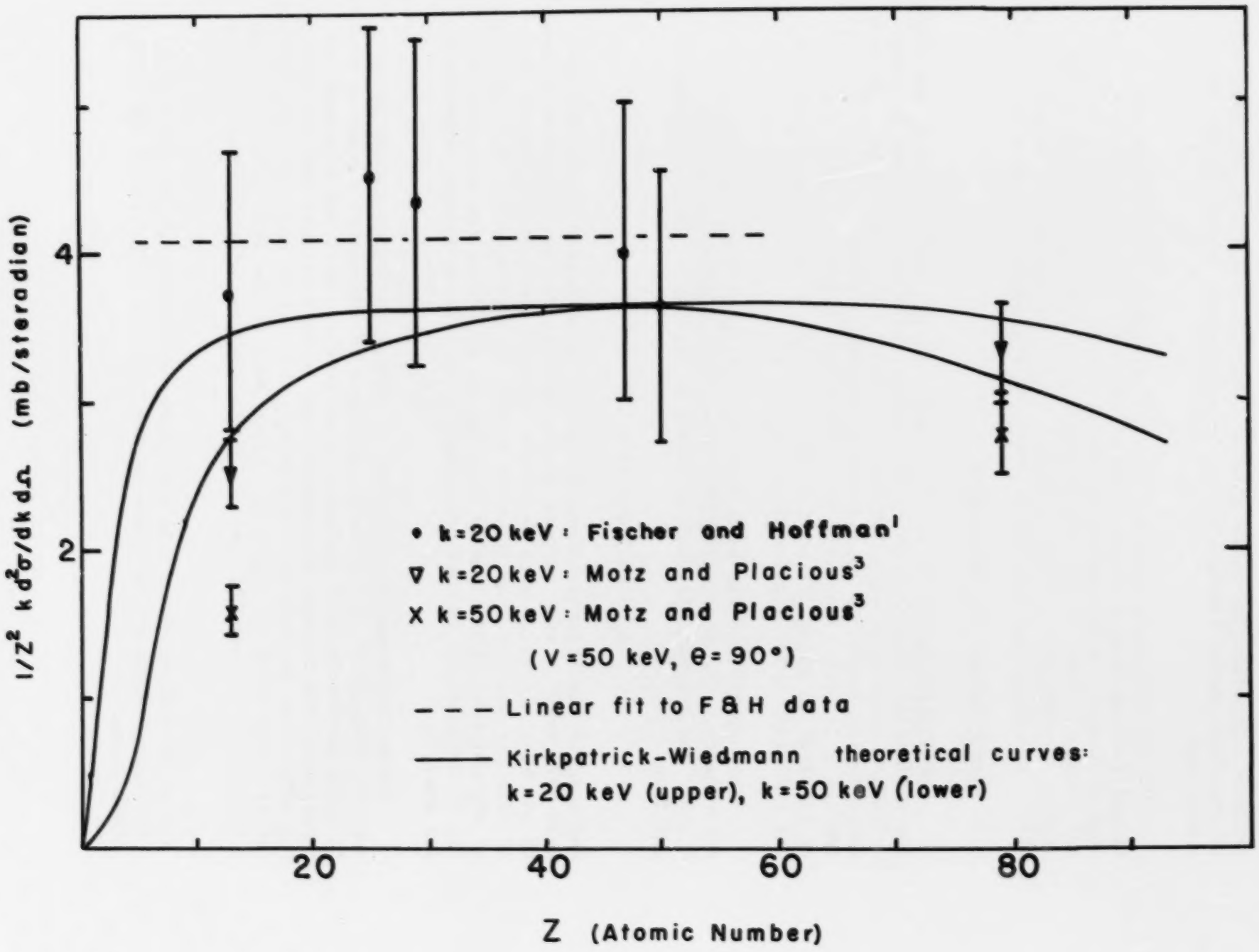

Figure 2. Z-dependence, at fixed V, k, θ.

(3), it is disappointing that they are in such poor agreement and indicative of the need for further absolute cross section measurements.

Amrehn and Kulenkampff (6) noted a Z dependence in the slope of the photon energy distribution (with a steeper negative slope for small Z). This would imply that the Z^2 proportionality does not hold for all k. Since in 1961 Kulenkampff and Ross (2) cast considerable doubt on the validity of the earlier results of Kulenkampff and his coworkers, this dependence is suspect as are the other conclusions of Amrehn noted above. The same dependence (i.e., steeper negative slope with decreasing atomic number) however, was also seen by Motz and Placious (3) and earlier by Nicholas (11).

Motz and Placious are the only experimenters whose results are not compatible with the bremsstrahlung angular distribution being independent of Z. Earlier work by Honerjager (9) with Al and Ni had suggested the possibility that the angular distribution might be broader at higher Z, but this could also have resulted from greater multiple scattering in the particular targets being used. Motz and Placious used Al and Au targets and obtained definite confirmation of this broadening, as seen in the section on θ dependence.

There is a paucity of data on most of the Z dependences. In particular, the work of Fischer and Hoffman should be extended to higher and lower atomic numbers to test the divergence from a Z^2 behavior and explain the discrepancies between references (1) and (3). It might also be useful if the measurements were expanded to include a greater density of atomic numbers in order to investigate any possible fine structure. Likewise, the variation in slope of the energy dependence and the change of the angular distribution with Z require further work because of the discrepancies among the results of the previous experiments.

3.2 VOLTAGE (V) DEPENDENCE

Very little thin-target work has been done concerning the dependence on incident electron energy (electron gun voltage). Early thick-target experiments (19-22) indicated that the total thick-target intensity was proportional to the square of the voltage and, at a fixed k, proportional to V; i.e., the relation obtained at fixed k was

$i_k = C\,(eV - k)$, (C some constant independent of V, e the electron charge)

For fixed k, the formula for the intensity from a thickness dx can be obtained by differentiating:

$i_k\,dx = eC\,(dV/dx)\,dx$ (assuming C independent of x)

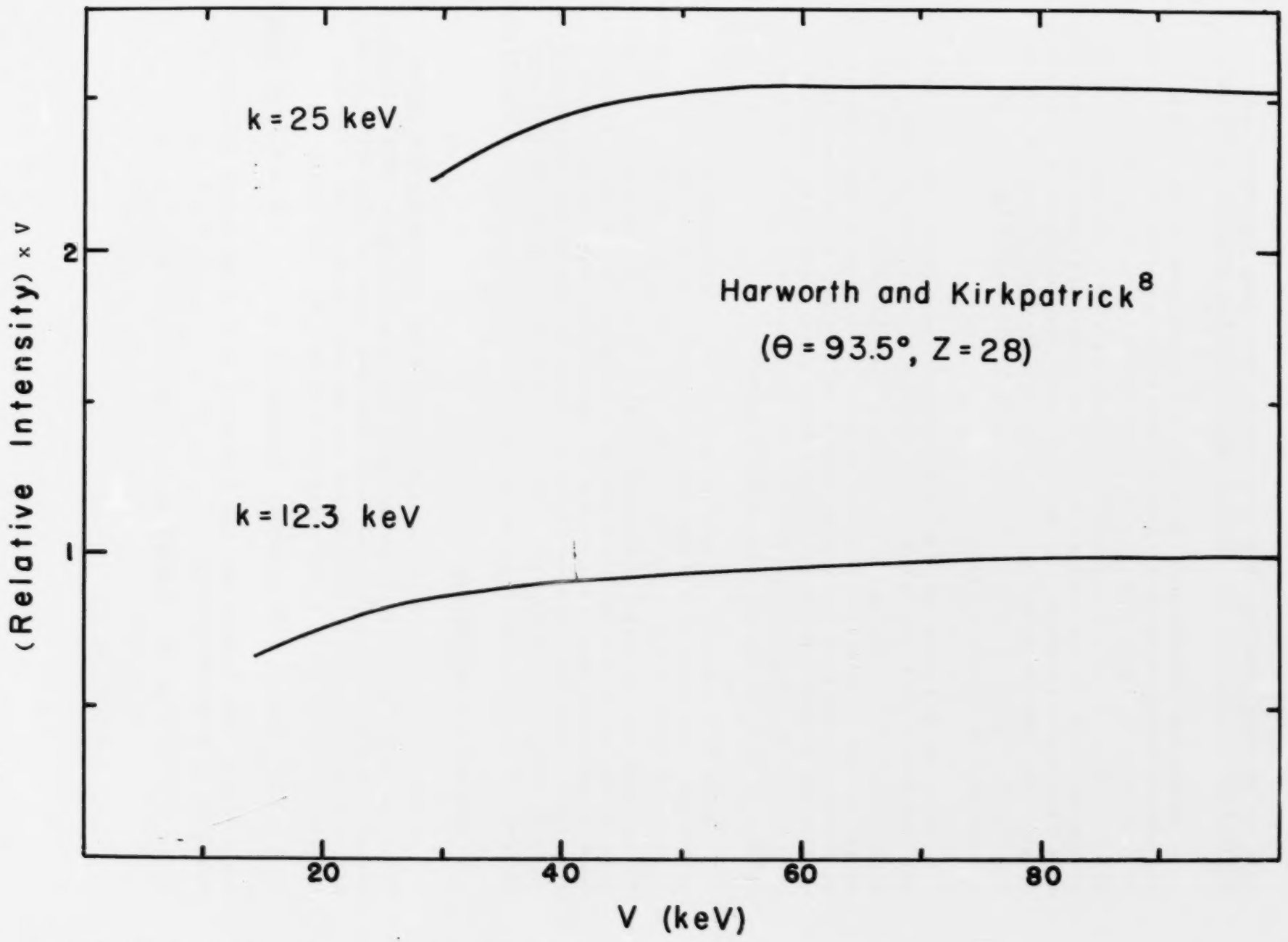

Figure 3. V-dependence, at fixed Z, k, θ.

and since dV/dx has been found to be approximately proportional to 1/V (Thompson-Whiddington Law (12)), one can conclude that for fixed k the thin-target intensity will decrease as 1/V.

Harworth and Kirkpatrick (8) used a thin Ni target for V from 12 to 180 kV and used filter combinations of Ag-Pd and Se-As to provide "monochromatization" (k = 25 keV, k = 12.3 keV, θ = 93.5°). They obtained quite good agreement with a 1/V dependence. Their results are shown in figure 3, where the product of V and the relative intensity is plotted as a function of V, normalized to 1.0 for the k = 12.3 keV curve at V = 100 keV. A true 1/V dependence would result in a horizontal straight line. Apparently the falloff is less than 1/V near the high frequency limit but quickly approaches that dependency, especially for large k. There is some question, however, whether their targets were sufficiently thin to give reliable results, especially for V less than 50 keV, where the deviation from 1/V behavior is seen. Kulenkampff (12) had previously shown that the falloff is different at different angles, being about at its steepest for $\theta = 90°$. This implies that the 1/V falloff does not hold at all angles, and that if it does hold at 90°, the cross section integrated over all angles decreases more slowly than 1/V.

This early work by Kulenkampff and later research by Honerjager (9), Bohm (10), and others (13-15) showed that the angular distribution changed as the voltage increased. The intensity maximum moves forward toward smaller angles as V increases, as is shown in figure 4. This is a relativistic effect which modifies the simple dipole radiation pattern. The distribution also appears to become more peaked with increasing V.

None of the more recent articles treat the V dependence specifically. Further work is needed to ascertain this dependence in our energy region for all of the quantities mentioned above. The work on the change in position of the forward maximum is the only very satisfactory result to date.

3.3 PHOTON ENERGY (k) DEPENDENCE

The bremsstrahlung energy spectrum has been investigated frequently, and the experimentally determined shape has changed substantially since the original experiments. In fact, the present conception of the spectrum dates from the late 1950's.

Early thick-target work showed the spectrum to have the form $i_k = C(k_o - k)$ as noted in the previous section. Using certain simple assumptions, this was shown (23) to imply that for a thin target the intensity would be constant for $k<k_o$, and zero for $k>k_o$; that is, i_k = constant up

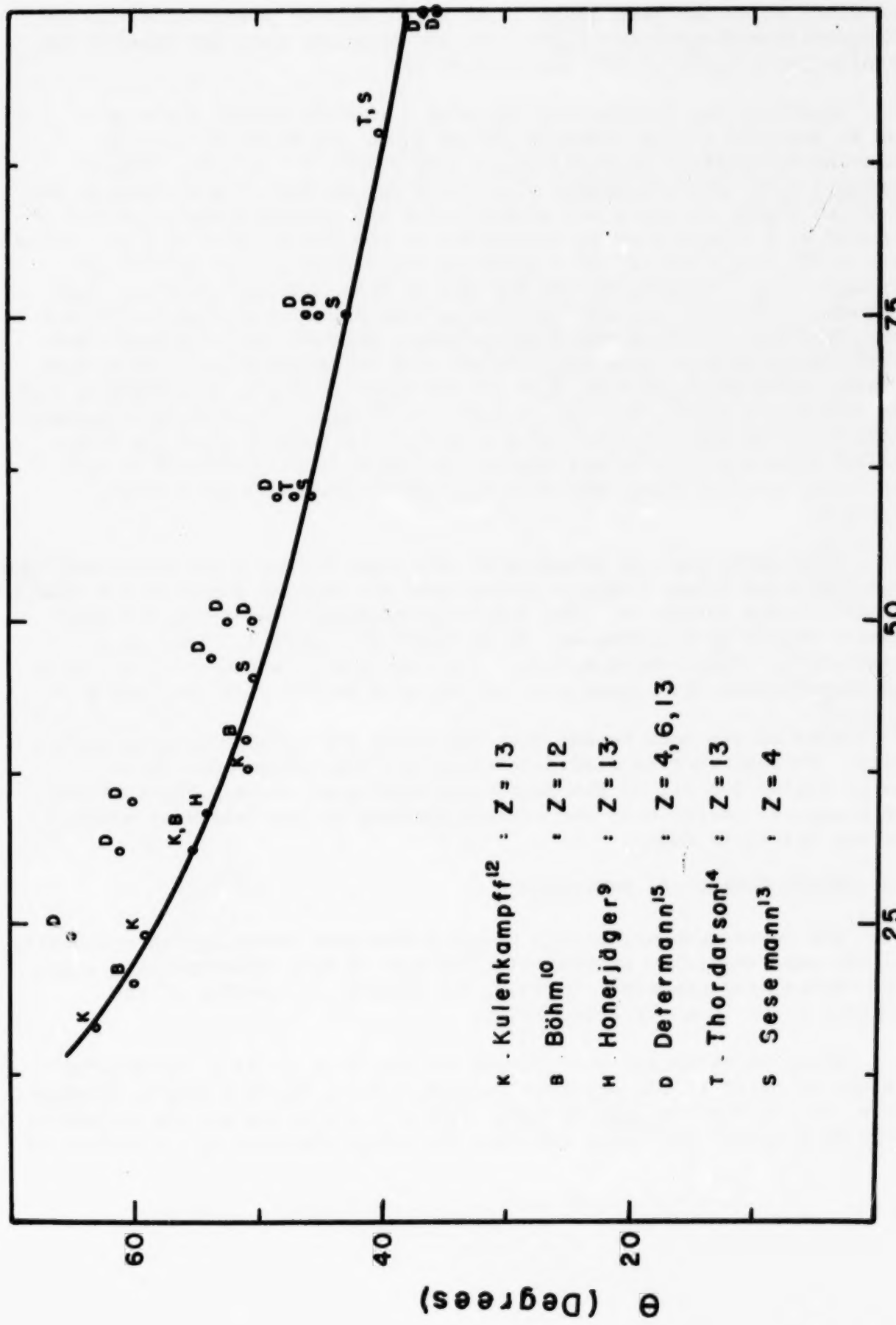

Figure 4. V-dependence of angle of maximum intensity.

to the high-energy cutoff at $k = k_o$[3] required by conservation of energy (Duane-Hunt Law). Thin-target experiments before 1940 were consistent with this form. A series of papers by Kulenkampff and his associates in the mid-50's reported nearly flat distributions at $\theta = 90^o$ and intensities increasing with decreasing k at angles near 0^o and 180^o. Later, however, it was discovered that these results had been distorted by a pulse pileup problem in the detection system. Kulenkampff and Ross (2) reported that the actual spectrum was much more sharply peaked toward small k than those published previously, and this was in agreement with Motz and Placious' results shown in figure 5.

From these latter two experiments in the late 1950's it is evident that the energy spectrum is peaked toward small k with a marked flattening as k increases. No experiment has found any evidence for a "turn over" at the boundary frequency; i.e., the spectrum appears to approach a limit value at $k = k_o$ (fig. 5). The shape of the spectrum varies with the angle of photon emission, being steepest at the intensity minima at $\theta = 0^o$ and $\theta = 180^o$. This variation with θ does not seem to have been explored very thoroughly.

It should be noted that effects of the characteristic radiation of the target material must be accounted for. The experimental spectrum consists of the superposition of the fluorescence lines upon the continuous bremsstrahlung spectrum. These lines are not evident in figure 5 because the aluminum K x rays would appear at 1.5 keV. For the heavier elements, however, the fluorescence radiation effects must be subtracted from the experimental distribution in order to obtain the bremsstrahlung energy spectrum.

3.4 PHOTON ANGLE (θ) DEPENDENCE

Probably most experimental attention has been devoted to the angular distribution of the intensity. Its general form has been known since the early work of Kulenkampff (12), who studied it as a function of tube voltage and photon energy. The radiation is emitted in a hollow cone in the forward direction, with its maximum at about 50^o (fig. 4) and minima at 0^o and 180^o. The intensity maximum is seen to move toward smaller θ and the angular distribution to become narrower as the voltage is increased (as mentioned earlier) and to become broader as k decreases. Figure 6 illustrates the broadening for high Z and low k/k_o. Note that the position of the forward maximum of i_θ also appears to shift toward larger values of θ as k/k_o decreases. Kulenkampff (12)

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[3] $k_o = eV\,(M_N/(M_N + m_e + eV - p_e \cos\theta)) = eV$ (to within present experimental error), where M_N, m_e, and p_e are the nuclear mass and electron mass and momentum.

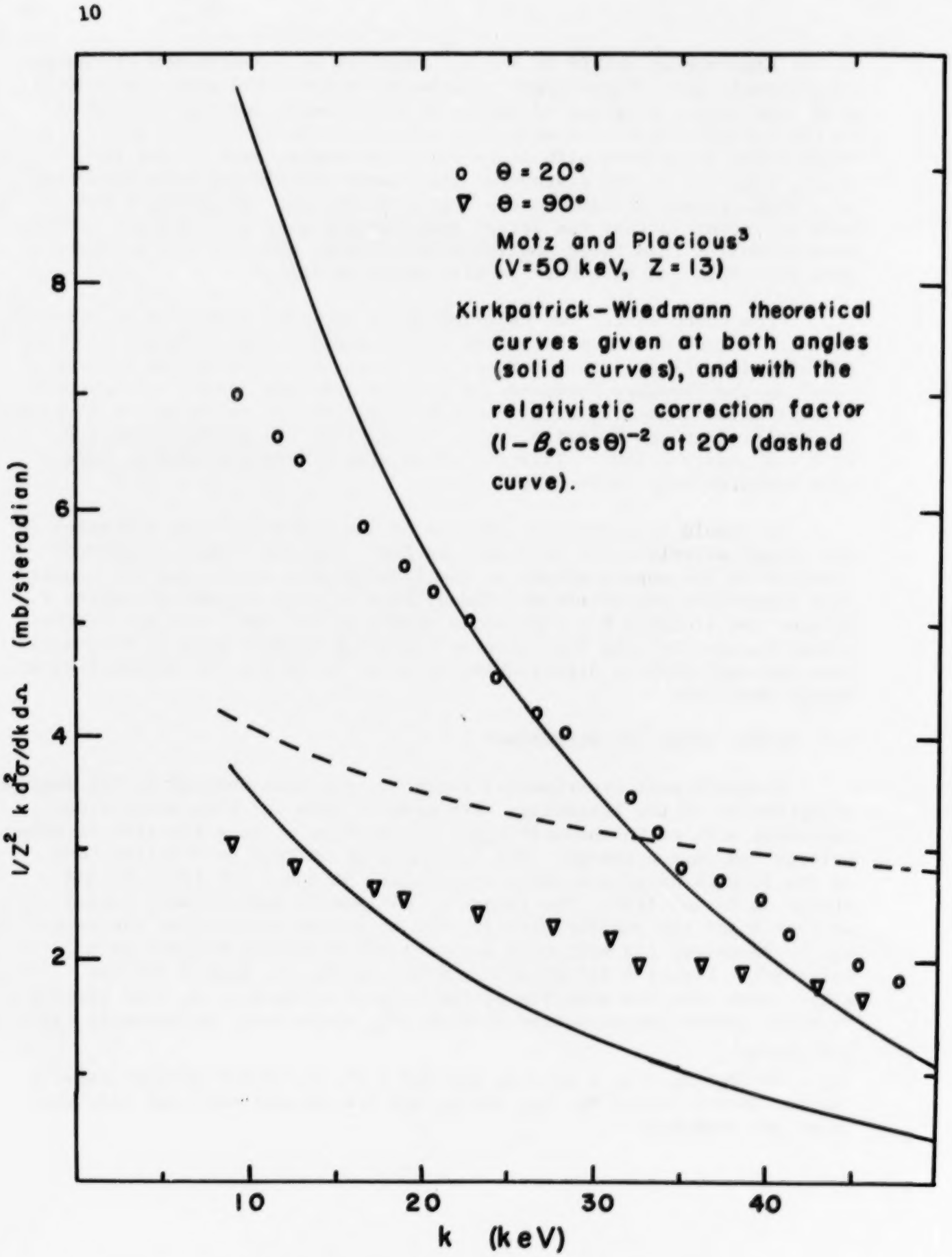

Figure 5. k-dependence, at fixed Z, V, θ.

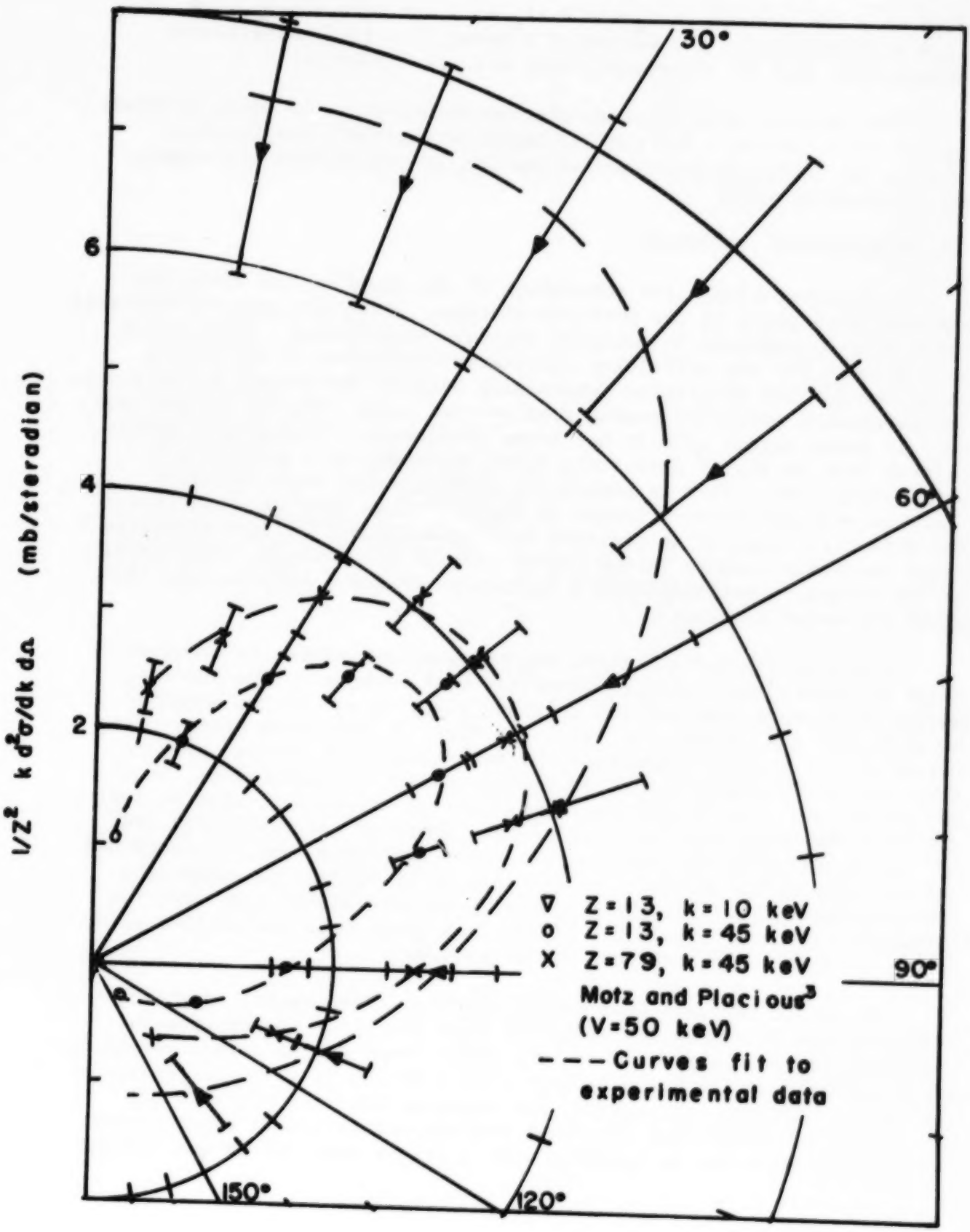

Figure 6. θ-dependence, at fixed Z, V, k.

noted that the maximum of $i_\theta \sin\theta$ ($i_\theta\, d\Omega$) was independent of θ, the sin θ factor shifting the maxima of a broad, low k/k_o distribution farther than that of a narrower, high k/k_o distribution.

Considerable work has been done on determining the bremsstrahlung angular distribution. The results could be improved considerably, however, by using new experimental techniques and by making a single, more exhaustive study.

3.5 EXPERIMENTAL TECHNIQUE

A somewhat simplified conception of the experimental situation may have been given in the previous section. There are many difficulties which must be resolved in carrying out such experiments. Corrections must be made for the efficiency and energy resolution of the photon detector, for the filtration intervening between the target and detector, for background radiation coming from sources other than the target, and for the thick-target effects mentioned previously. Preparing a sufficiently thin target of accurately known thickness is a particularly painstaking task. This is especially difficult for small incident electron energies since a target is thick or thin only in comparison to the effective range of an electron in that material, and the effective range decreases roughly as the inverse of the gun voltage. Impurities in the target, especially high Z impurities in low Z targets, may also yield erroneous results.

Experimental distributions may be presented either in absolute or relative terms; i.e., either normalized with respect to the absolute number of photons produced per incident electron per target atom/cm^2 or with just the relative shape of the distribution being given. The latter is, of course, experimentally much simpler to obtain; however, since DEP is basically concerned with dosimetry considerations, it is not sufficient. It is therefore particularly unfortunate that so few absolute determinations have been made. Those of references (1) and (3) are practically the only reliable ones available, and, as mentioned before, they differ markedly at the only point subject to comparison (the reference (1) value lying nearly 50 percent higher than that for reference (3)---see figure 2). There is a great need for further study of the absolute bremsstrahlung cross sections.

It should be noted that vastly improved experimental apparatus is available now in comparison with that used in all of the experiments mentioned above. In particular, the solid-state photon detection instruments commonly used today have more than a factor of 10 better energy resolution than previous types. For example, Motz and Placious (3) quote an 8-keV resolution for their NaI(Tl) scintillation spectrometer (at 22 keV) which may be compared with a better than 300-eV resolution

obtainable today with a Si(Li) detector. Moreover, the improved data acquisition systems now available allow much greater quantities of experimental data to be collected efficiently than was previously possible. These technical advances have made much of the earlier work obsolete.

4. THIN-TARGET BREMSSTRAHLUNG THEORY: LITERATURE SURVEY

A study has also been made of the current state of the theoretical understanding of bremsstrahlung production. If all of the relevant distributions could be precisely calculated, there would be little reason to carry out further experimental work. Unfortunately, the theoretical situation is even less satisfactory than the experimental one. There are nonrelativistic approximations, which may be valid for energies up to a few keV, and extreme relativistic solutions, which should be adequate above a few MeV, but the region of interest presents a quite complicated situation to the theoretician. A review of the theoretical situation was published by Koch and Motz (28) in 1959, stressing Born-approximation formulas stated to be correct only to within a factor of two below 2 MeV. Little progress has been made since then.[4]

Between 10 and 100 keV β varies from 0.2 to 0.55 and γ from 1.02 to 1.20.[5] Thus, even at energies as low as 10 keV, the nonrelativistic condition $\beta \ll 1$ is not well satisfied, and depending upon the actual dependence on β and γ, the real cross section may differ markedly from the nonrelativistic expressions. In one respect, this deviation from the nonrelativistic calculation has ample experimental confirmation. This is the forward inclination of the angular distribution from 90° (nonrelativistic result) toward smaller angles. Even at 10 keV, the maximum in the angular distribution is shifted nearly to 70°.

The basic difficulty is the complexity of the calculations involved. It is thought that the electromagnetic interaction occurring is well understood; however, the exact calculation of a distribution is not possible with the present mathematical tools. Only by making simplifying assumptions can solutions be obtained. Even the basic Sommerfeld, nonrelativistic problem of a "slow" electron incident upon a bare nucleus requires fairly difficult computer numerical integration techniques for solution. Kirkpatrick and Wiedmann (30) have carried out

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[4] Work presently being carried out by Tseng and Pratt (29) may radically alter this situation. They are performing an exact relativistic numerical calculation, with screening effects included.

[5] $\beta = V/C$, $\gamma = (1-\beta^2)^{-1/2}$ are the usual relativistic parameters.

computations for the nonrelativistic Sommerfeld theory, and curves calculated from their formulas are shown in figures 1 and 5. Fairly good agreement is attained for the Z dependence (fig. 1), but the experimental points are not in very good correspondence with theory for the energy spectrum (fig. 5). Relativistic considerations are then typically treated by multiplying the nonrelativistic results by various ad hoc correction factors.

Other corrections may also be important. For low-energy bremsstrahlung photons the screening provided by the atomic electrons must be considered. Sauter (31) has given a solution for $k = 0$, but otherwise the screening corrections are very uncertain.

Obviously, considerable work remains to be done on the theoretical situation. It is remarkable that the present calculations agree as well with experiment as they do, since they have of necessity been carried out beyond the domains of validity of their basic assumptions. Further investigation of the theoretical literature is underway, and results will be summarized in a later report.

5. DIVISION OF ELECTRONIC PRODUCTS EXPERIMENTAL PROGRAM

In view of the deficiencies in the theoretical bremsstrahlung calculations and the paucity of experimental data, further experimental work is required. The Radiation Measurements and Calibration Branch of DEP has begun an experimental program to correct these deficiencies. The basic process to be studied is as outlined in section 2. A beam of electrons is accelerated through a potential difference and strikes a target of atomic number Z material, with the energy spectrum of the resultant bremsstrahlung photons being measured at an angle θ with respect to the incident beam. A schematic diagram of the experimental apparatus being used to accomplish this is given in figure 7. A high-voltage power supply (A) provides a constant high voltage to an electron gun (B), yielding an electron beam which impinges upon a thin target (C) inside a vacuum chamber (D). Most of the electrons are neither scattered nor absorbed but pass through the target and are collected in a Faraday cup (E). The bremsstrahlung photons leaving the target at an angle θ to the incident electron beam are detected by a solid-state detector (F).

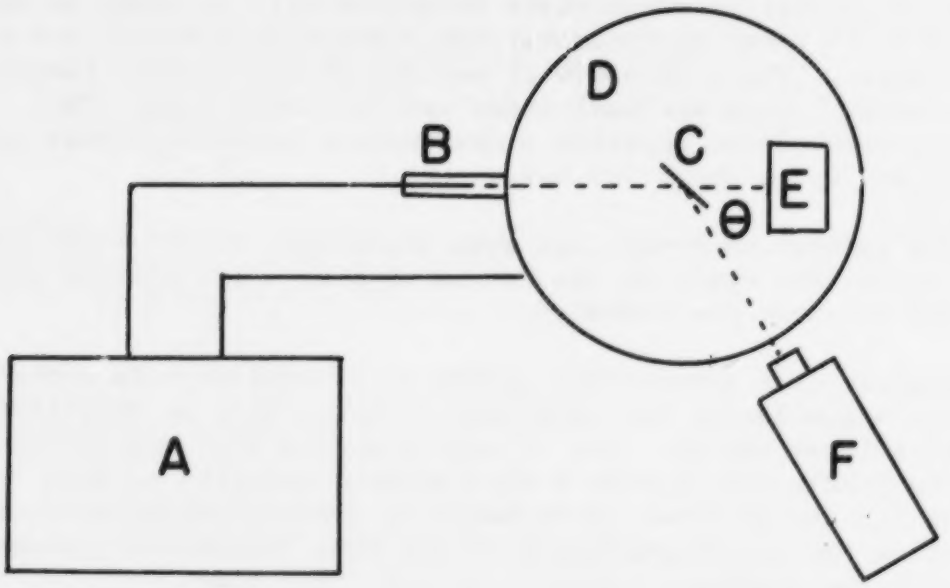

Figure 7. Schematic diagram of experimental setup.

The specific equipment being used for these purposes is described briefly below:

A. Universal Voltronics Corporation regulated high-voltage supply, Model BRE-60-50-R2, 10-60 kV operating range, 50 mA maximum current, estimated $\pm$ 0.2 percent calibration accuracy, less than 0.01 percent rms ripple.

John Fluke Mfg. Co., Inc., power supply, Model 430 B, 10-30 kV operating range, 50 mA maximum current, $\pm$ 0.25 percent calibration accuracy, less than 5 mv rms ripple.

B. Present electron source capability is limited to two television electron guns operable to 24 kV (Superior Electronics Corp. SE83, Griffith Electronic, Inc., GE 50).

C. Thin targets will be vacuum deposited on Mylar or on colloidion films. Atomic absorption spectrometry and electrobalance techniques will be used to determine target thickness.

D. Bench-top high-vacuum system, Norton Co., Vacuum Division, Model 3401, capacility to 10^{-8} Torr.

E. A Faraday cup--ammeter system for collection and measurement of beam current is to be constructed.

F. Two high-quality solid-state detectors will be used, an Ortec 8113-10$^{Ge(Li)}$ x-ray spectrometer and a Kevex 301D Si(Li) x-ray spectrometer. These have 400 eV and 250 eV resolutions respectively (full width at half maximum) under optimum conditions. This detector combination provides a measurement capability down to 1.5 keV and up to about 250 keV.

The experimental equipment has been assembled, except where noted above, and tests have begun on the vacuum chamber, high voltage power supplies, and electron gun assembly.

An automatic data acquisition system to be used in this experiment for data accumulation and experiment control will be described in detail in a later report. Use of such a system will enable this experiment to handle efficiently a much greater quantity of data than was possible for the previous experiments on bremsstrahlung production. This will allow the interdependences of the four fundamental parameters (Z, V, k, θ) to be studied in detail for the first time.

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